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ABSTRACT

The grant from Defense University Research Instrumentation Program was used to purchase and install diamond wire saw and vacuum furnace at Advanced Powder Processing Lab at MAE Department, UCSD.

The installation of this equipment added very important components to the existing equipment at Advanced Powder Processing Lab at MAE Department, UCSD which now has Hot Isostatic Pressing unit, Warm and Cold Isostatic Pressing units, 2 vacuum furnaces (low and high temperatures), diamond wire saw, glove box and Struers polishing and cutting machines. Currently they are actively used for processing of high gradient metal/ceramic porous composites for MURI Program. Addition of high temperature vacuum furnace opens a new technological route (sintering + HIP) for processing of covalent ceramics for ballistic applications. It will also enhance ability to educate the future engineers for industry oriented on ceramic armor and other applications. Diamond wire saw helps to overcome extreme difficulties of sectioning of composite targets with ceramics inside and with remnants of penetrators usually made from high strength materials.

Advanced Powder Processing Lab at MAE Department, UCSD now is able to solve efficiently many problems connected with processing of powder-based homogeneous and heterogeneous materials for DOD needs including armor structures and other applications.

I. EQUIPMENT ACQUIRED AND SUMMARY OF RELATED PROJECTS

I.1 Vacuum Furnace

Company's name: *Thermal Technology INC.*
Model No.: *HTG-9020-23*
Furnace Serial No.: *F0005010*
Power Supply Serial No.: *C010-0005*
Working Maximum Temperature: 2200^{0}C
Required Air Supply Pressure: 60 PsiG
Required Cooling Water: 16GPM Minimum
Required Power Supply: 480V, 3Phase, 125A, 60Hz
Cost: 147,476.35
Matching funds 22,154.99 were additionally provide by UCSD to purchase this equipment

The vacuum furnace was purchased and successfully installed in Advanced Powder Processing Lab at MAE Department, UCSD (see Figure 1). Currently the vacuum furnace is under final troubleshooting stage. The water-cooling system was installed and tested.

This furnace will be used to process composite samples with incorporated B_4C plates in July of this year as part of the current MURI program. The PI of this proposal is a Co-PI of MURI project with ARO (MURI DAAH 04-96-1-0376). The main thrust of the research in this program is focused on the optimization of processing of damage tolerant light-weight armor materials based on the results of dynamic testing of material properties, ballistic testing of armor structural elements and modeling. It is of great interest to explore new concepts involving behavior of highly heterogeneous structures under high-strain-rate conditions effecting penetrator / target interaction.

This device will enhance the quality of research due to the opening of new technological route: vacuum presintering + containerless HIPing of B_4C and other covalent armor related ceramics and composites. High temperature vacuum furnace can be used also for annealing process. It will allow the optimization of grain size and

porosity of B_4C plates and tubes, which will be incorporated into high gradient structure using powder processing with existing Hot Isostatic Press (HIP). It will also allow us to develop ceramic/polymer composites based on high-strength, high porosity B_4C.

Densification of pure boron carbide is extremely difficult due to high fraction of covalent bonding between the boron and carbon atoms. The pore eliminating mechanisms such as volume and grain boundary diffusion are effective only at temperatures above 2000^0C. At low temperatures surface diffusion, evaporation and recondensation are the only mechanisms that contribute to the neck formation, pore coalescence and rounding of the particles. But they alone can not densify the material. Boron carbide can only be densified (without pressure application) by starting with very fine particles (size smaller than one micron) and with low oxygen content at temperatures in the range of 2250-2350 ^{0}C.

HIPing of boron containing materials creates a special technological difficulties with the canning material. The metal containers usually react with boron to form metal borides. Use of silica glasses with high softening temperature causes diffusion of boron from the outer layers of the specimen into the glass. It strongly influences the viscosity and the glass transformation temperature. In some cases, boron oxide gas may be released from the sample resulting in the blowing of the container.

No results are published on HIPing of high porosity ceramics. At the same time they may be very useful in light armor applications being filled with polymers.

The vacuum furnace will be used in the following technological steps:

- High temperature degassing and reduction treatment of the material prior to HIPing;
- Sintering of B_4C to closed porosity for containerless HIPing;
- Improved microstructural control through high temperature annealing;
- Sintering of B_4C to open porosity prior to HIPing and high-pressure impregnation by polymers.

This equipment will effectively shorten the circle for optimization of the high gradient materials with covalent ceramics: *processing—dynamic testing—constitutive modeling—ballistic testing—numerical modeling of penetration—optimization of processing*. It will also enhance the research related to education and will be used in graduate course MAE-270 (Mechanics of Powder Processing) developed by PI at UCSD and for training of graduate students in the Mechanical and Aerospace Department and in the UCSD Materials Science and Engineering Program. Two PhD students (J. Shi and H. Chen), who were co-advised by the PI are currently employed in armor related research activity in Ceradyne and Cercom respectively.

For the first step, this vacuum furnace will be used to prepare a plates from B_4C powder to replace Al_2O_3 plates that are currently used inside the composite samples of

high gradient armor developed in the MURI program. Vacuum furnace was chosen as important equipment to fulfill this goal because high temperatures (above 2000 °C) are the requirement for sintering B_4C powder before we go for the next step - HIPing. The designed procedure for this specific project is the following:

1. Cold isostatic pressing of loose B_4C to obtain a relatively strong body.
2. Sintering of B_4C in vacuum furnace to get a sample with closed porosity.
3. Containerless hot isostatic pressing of B_4C in order to achieve a high quality B_4C disc with regulated porosity.
4. B_4C disc about 30-mm diameter will be placed into Ti-6Al-4V PREP-nonmilled powder covered with protective layer and vacuum encapsulated.
5. Hot isostatic pressing of the Ti-6Al-4V based samples with B_4C plate inside.
6. Ballistic testing of the composite with B_4C discs of different porosity inside.

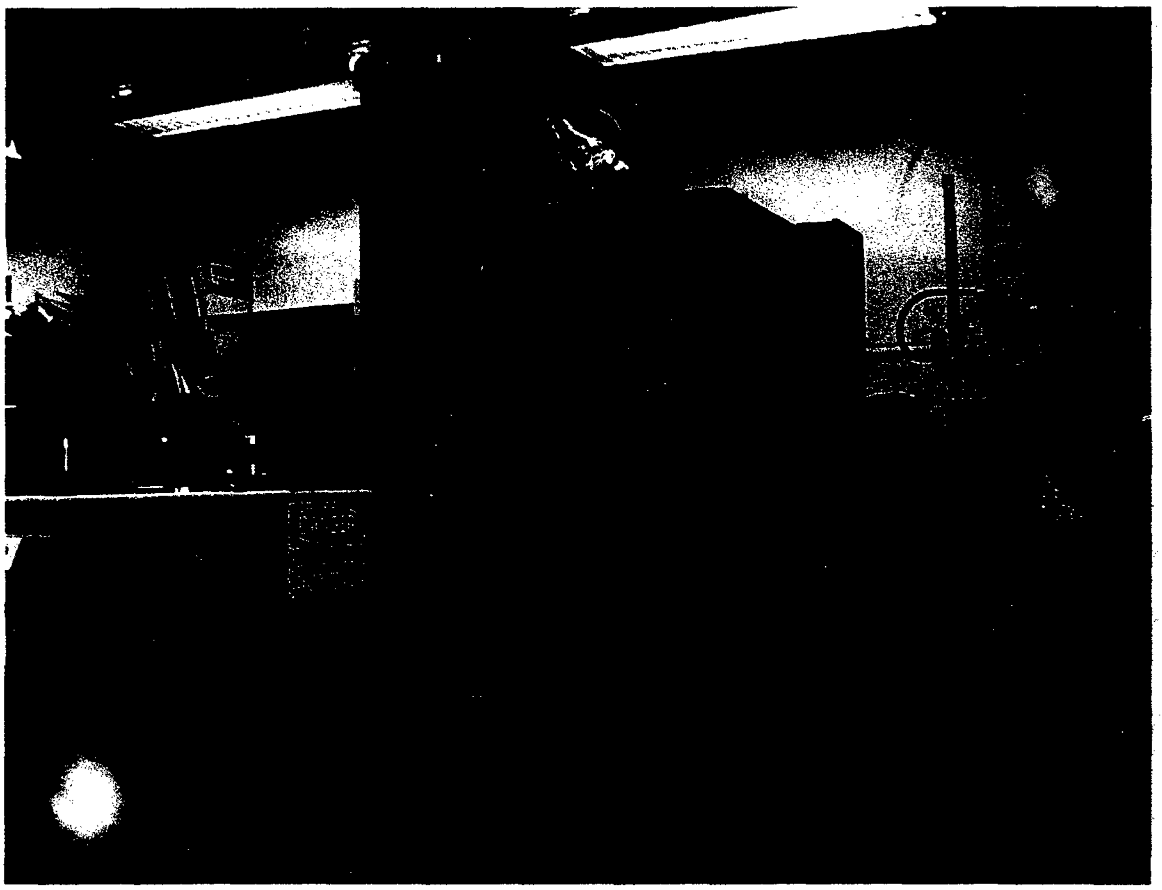

Figure 1. Vacuum furnace installed in Advanced Powder Processing Lab at MAE Department, UCSD.

I.2 Diamond Wire Saw

Company's Name:	*Laser Technology West Limited*		
Model No.:	*228120;*	*Serious No.:*	*1283*
Control Box No.:	*2. 0. 3;*	*Serious No.:*	*0005*
Version:	*2.0.3 SN 1283*		
University Control No.:	*006037525*		
Cost: 49,683.53			

The diamond wire saw was purchased and successfully installed in Advanced Powder Processing Lab at MAE Department, UCSD (see Figure 2). Unfortunately this device underwent almost 4 months troubleshooting efforts before actual cutting was done. The capstan was vibrating too much and was replaced by a new one. The magnetic sensor for controlling the target bow was damaged during the repair and a new one was installed. The control box was shipped back two times to the company because some malfunction of the program controlled cutting. Nevertheless, the Laser Technology West Limited provided all necessary support to successfully overcome the problems.

High gradient composite armor materials after ballistic test incorporates ceramics, high strength metallic alloys from target and a remnants of the penetrator (see Figure 3). Before installation of the diamond wire saw we experienced enormous difficulties to prepare samples from such materials for microstructural research. The only way to make cut of this highly heterogeneous mixture of materials was water jet. Additionally to being a very expensive procedure, water jet cutting inevitably creates a very wavy surface, removing an important structural details of penetrator/target interaction crucial for material investigation and modeling. These difficulty does not exist after we added a diamond wire saw to our experimental capability. As a water jet method, it is not a cheap technique, but it is the only method capable to cut practically any combination of material with minimal damage to microstructure.

There are the following advantages of diamond wire saw for cutting over EDM or water jet cutting and conventional machining:

- High precision cutting of the heterogeneous, high strength comminuted brittle samples after penetration tests.
- Composite samples can be cut without essential removal of the material.
- No conductivity of the sample required for machining.

- The same machine can be used to prepare the smaller samples for Hopkinson bar or for compression (tension) test of materials with very good precision.
- The surface of the sample after cutting is close to that of the polished one.
- Cutting without heating up of the sample and little structural damage of the sample.
- High edge sharpness even with the cutting of the brittle materials
- No coolant or cutting fluid is required for cutting.

The cutting with the wire saw can be used for preparation of samples from metals, ceramics and high gradient composites of varying compositions as the surface after the cutting is smooth and uniform. The size of the sample can have a height go up to 60mm and can have a width go up to 150 mm.

The use of diamond wire saw helps to reveal the details of fracture of tungsten rod penetrator, ceramic comminution, shear banding after the ballistic testing with minimal loss of material. This will provide a valuable information for the mechanisms of these processes. There is practically no other instrumentation that can do a reliable cut of peculiar mixture of materials created by ballistic impact of tungsten rod (or by other penetrators) with damage tolerant high gradient armor.

The example of the current application of the diamond wire saw is the cutting of recently developed high gradient composite materials in the frame of MURI program. The samples of such materials are prepared based on hot isostatically pressed Ti-6Al-4V matrix with embedded ceramic (alumina) rods and tubes filled with boron carbide powders. This structure may effectively push the long rod penetrator sideways and exhibits a self-trapping effect, which is shown in Figure 3 below.

After cutting with diamond wire saw B_4C powder was preserved practically intact inside Al_2O_3 tubes. Important elements of structural damage such as microcracking of the interfacial layer between Al_2O_3 tube/plate and Ti-6Al-4V matrix and forced shear localization induced by fracture of Al_2O_3 tubes on the early stages of penetration process were clearly shown even without polishing.

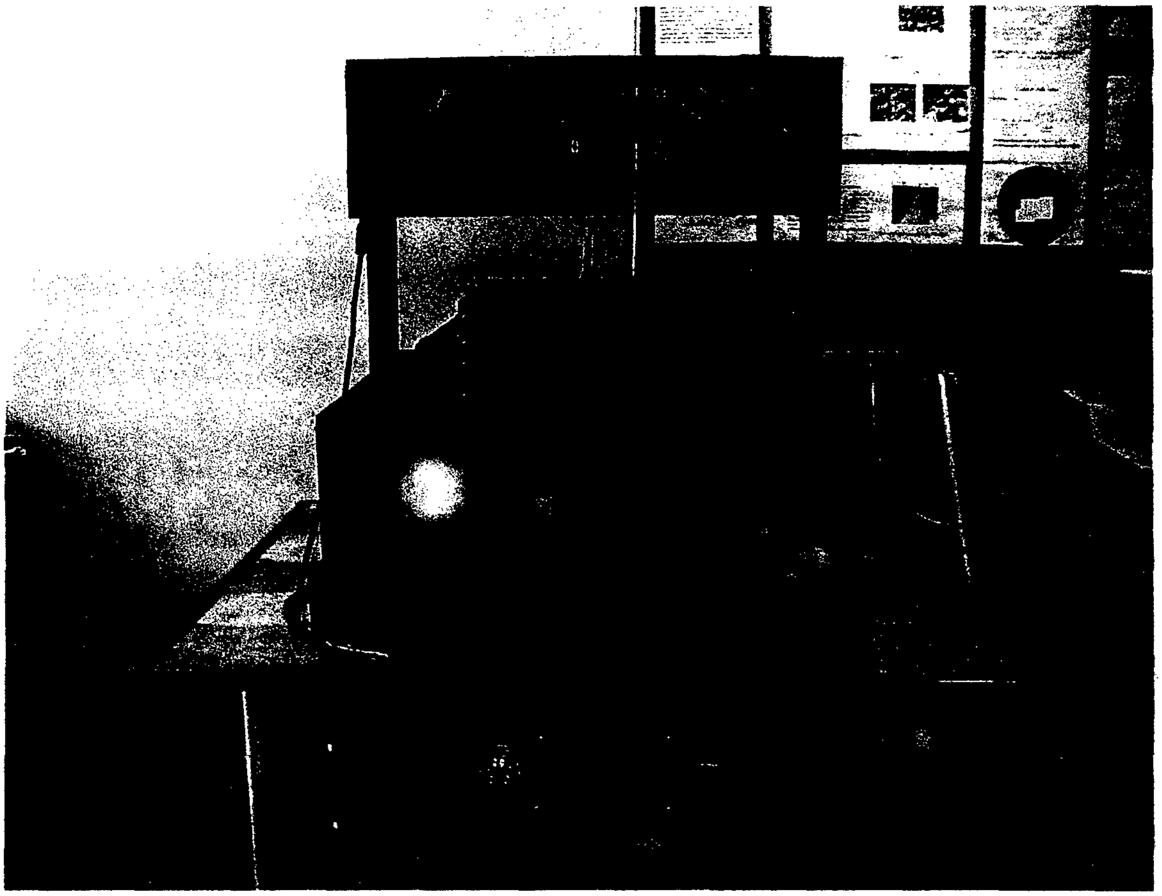

Figure 2. Diamond wire was installed in Advanced Powder Processing Lab at MAE Department, UCSD.

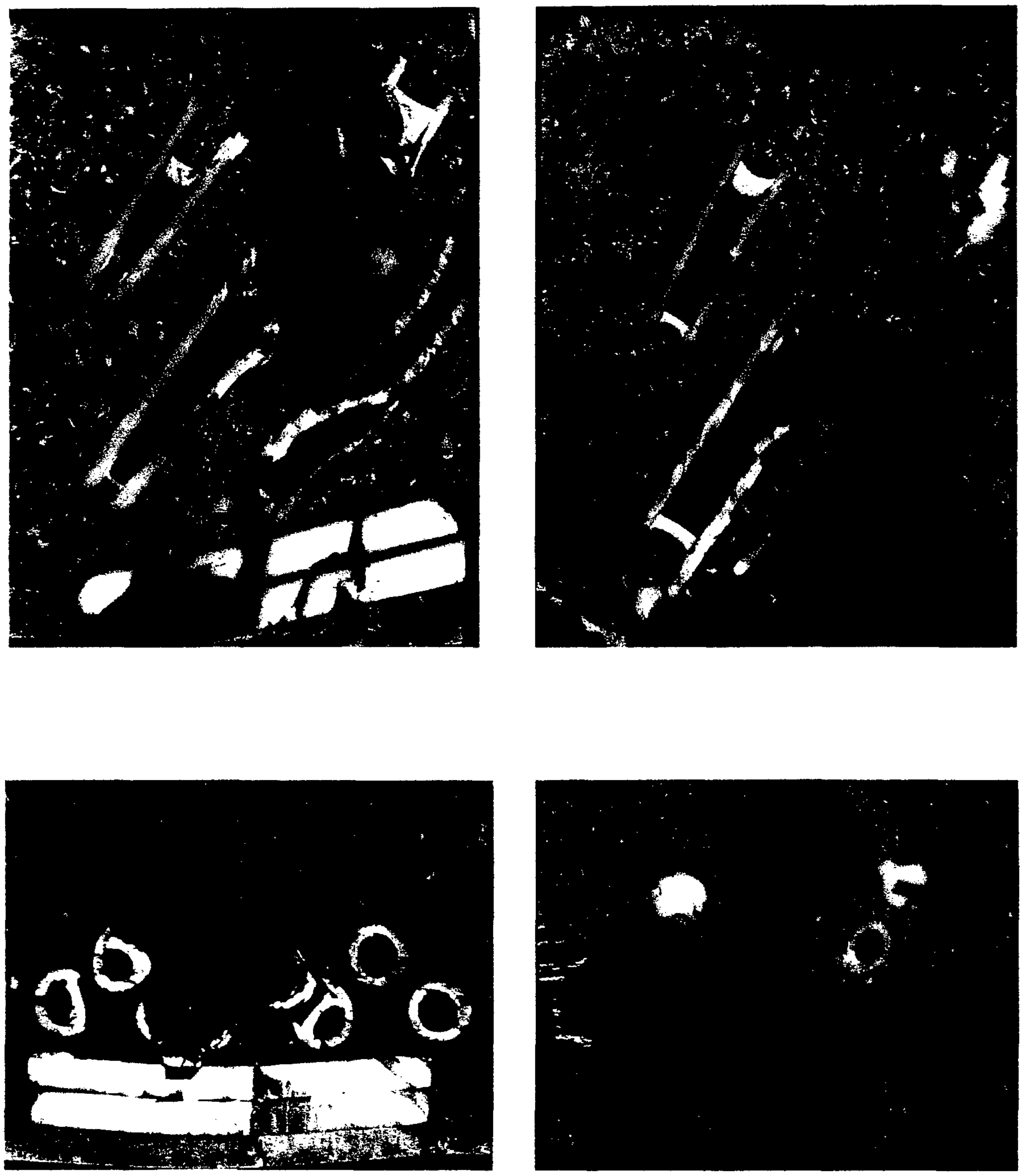

Figure 3. Samples of high gradient composite armor sectioned using diamond wire saw. Microstructural features of remnants of tungsten rod penetrator, boron carbide powder, forced shear localization initiated by collapsing alumina tubes in the Ti–6Al–4V matrix are well preserved after cut.

CONCLUSION

Two important devices (diamond saw and vacuum furnace) were purchased and installed in the Advanced Powder Processing Lab at MAE Department, UCSD using the grant from Defense University Research Instrumentation Program.

The installation of this equipment added very important components to the existing equipment at the Advanced Powder Processing Lab at MAE Department, UCSD which now has Hot Isostatic Pressing unit, Warm and Cold Isostatic Pressing units, 2 vacuum furnaces (low and high temperatures), diamond wire saw, glove box and Struers polishing and cutting machines. This equipment is actively used for processing of high gradient metal/ceramic porous composites for MURI Program. Addition of high temperature vacuum furnace opens a new technological route (sintering + HIP) for processing of covalent ceramics for ballistic applications. It will also enhance ability to educate the future engineers for industry oriented on ceramic armor applications.

Diamond wire saw is irreplaceable for sectioning of composite targets with ceramics inside and with remnants of penetrator. A clean cut of these targets with diamond saw is very important for microstructural analysis of ceramic comminution, penetrator damage and shear localization in the matrix.

Advanced Powder Processing Lab at MAE Department, UCSD now is able to efficiently solve many problems connected with processing of powder-based homogeneous and heterogeneous materials for DOD needs including armor structures and other applications.

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DEPARTMENT OF MECHANICAL AND
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July 9, 2001

Army research Office
Atten: AMSRL-RO-RI (Technical Reports)
P. O. Box 12211
Research Triangle Park, NC 27709-2211

Gentlemen:

RE: DAAD19-00-1-007
Final Technical Report

Please accept the enclosed "Final Technical Report" for the above referenced grant titled "Vacuum Furnace and Diamond Saw for Processing of Covalent Armor and Ceramics and Composites."

This report was sent to Office of Naval Research on June 25, 2001 as they were listed in the award as administering the award.

Sincerely
Vitali Nesterenko

dr

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June 25, 2001

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4520 Executive Drive, suite 300
San Diego, CA 92121-3019

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RE: DAAD19-00-1-007
Final Technical Report

Gentlemen:

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Sincerely,
Vitali Nesterenko